
2.2. Hardware development

2.2.1. Instrument upgrades

During the time since the initial receipt of the AMS, many improvements have been made to the instrument itself, in partnership with ARI. The net result of these has been to improve the quality and the scope of the data produced. Most of the development and implementation of the upgrades were performed at ARI, although work was performed as part of this thesis to evaluate the effectiveness of these. The exception is the inlet temperature control system (section 2.2.2.2.), which was entirely developed at UMIST.

2.2.1.1. Aerodynamic lens

The original aerodynamic lens design used in the instrument, described by *Jayne et al.* [2000] could focus particles of vacuum aerodynamic diameters between 70 and 700 nm efficiently (see section 2.1.1.). However, there are many particulates in the atmosphere of great interest below these sizes, so work was performed at ARI with the goal of developing an aerodynamic lens that could focus smaller particles. This work principally employed computational fluid dynamics and is presented by *Zhang et al.* [2002; 2004]. An aerodynamic lens using an improved design was fitted during 2001 (immediately prior to the Pacific 2001 campaign), offering a lower cutoff of 30 nm. This modification also involved changing the pinhole diameter from 120 μm to 100 μm , to reduce the pressure inside the lens, thereby reducing the defocusing of smaller particles due to Brownian motion. This change in lens design did not adversely affect the transmission of the larger particles; the most significant loss of large particles in both designs occurs at the pinhole used to control the flow rather than the lens itself.

The improvement to the particle transmission in the lower sizes can easily be seen when comparing the mass size distributions of the organic fraction from the four urban campaigns detailed in section 3.1 (figure 2.2.1.1.a). In all of these, an organic mode was consistently seen at sizes below 200 nm that corresponded to emissions from motor vehicles. In Edinburgh and the summer Manchester sampling periods, this mode extended down to only around 50 nm, as the older lens design was used in these campaigns. During the Vancouver and winter Manchester sampling, when the newer lens design was used, the mode extended all the way down to 30 nm.

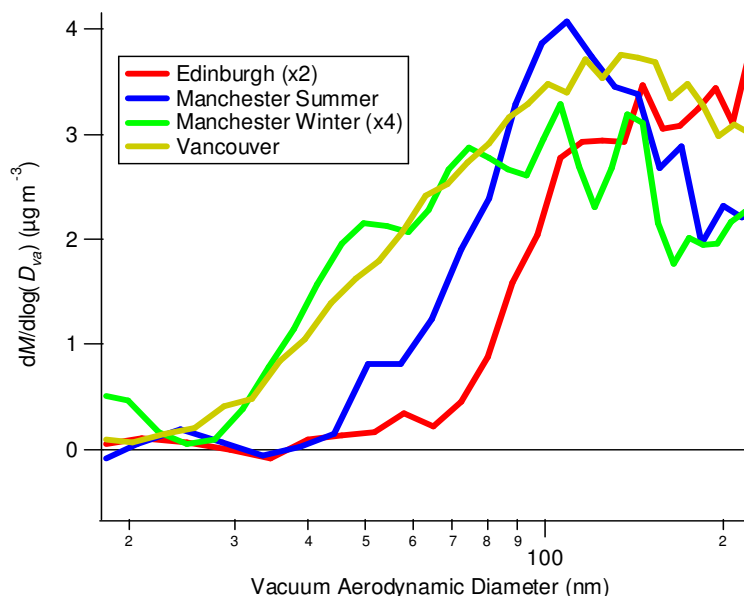


Figure 2.2.1.1.a. Evaluation of lens transmission during four field projects. The data have been scaled to facilitate the comparison. Edinburgh and Manchester during the summer used the older design while Manchester during the winter and Vancouver used the newer one.

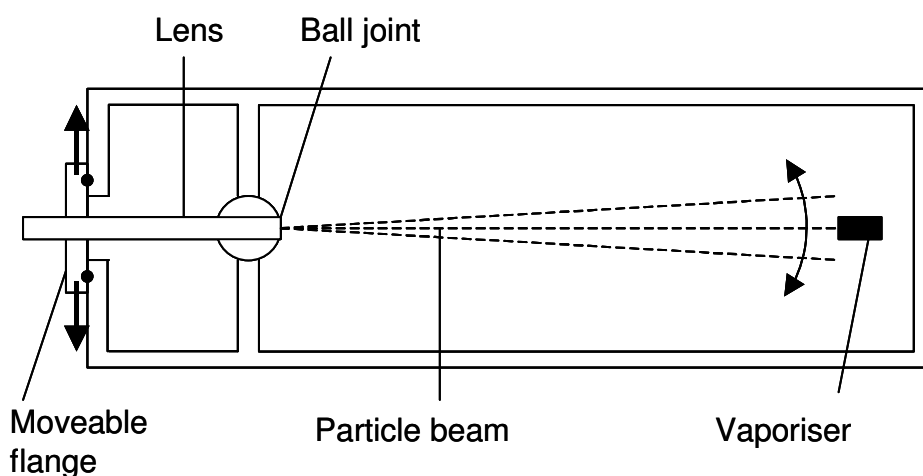


Figure 2.2.1.1.b. Basic schematic of the movable lens mount. The apertures between the lens and detection chambers have been omitted for clarity.

An additional modification performed at the same time involved mounting the nozzle end of the lens into a swivelling ball and socket arrangement and allowing some translational movement of the flange in which the lens is mounted in the front of the instrument. This allows the lens to be moved in two axes of rotation and means that the direction in which it can be pointed can be adjusted, as shown in figure 2.2.1.1.b. Previously, the lens had been fixed, which meant achieving good alignment was often troublesome and sometimes entailed moving the vaporiser itself.

Since this modification was made, an alignment check has been instituted as part of the setting up procedure in a deployment. To perform this, monodisperse ammonium nitrate particles (generated using a nebuliser or atomiser and size-selected using a DMA) are counted by the AMS and compared to a CPC sampling the same aerosol. If the lens is aligned correctly, the numbers should be roughly equal. The lens direction is manually walked across the vaporiser and the AMS collection efficiency is measured as a function of lens direction in a given plane. As pure ammonium nitrate particles are normally well focused, this manifests as a slightly smoothed top hat distribution, the plateau representing the points where the beam was hitting the vaporiser. If this is performed in both the horizontal and vertical axes, the centres of the distributions can be chosen to be the optimum alignment positions for the lens.

2.2.1.2. Vacuum system

One of the key factors that affects the sensitivity of the instrument is the quality of the vacuum within the detection region. Both the quadrupole and the electron multiplier work more efficiently at lower pressures, increasing the signal to noise ratio and decreasing the detection limits, which can in turn mean shorter averaging times can be used. Also, as discussed in section 2.4.2.6., if the background signals within the blocked spectra are reduced, the counting statistics of the subtracted signals in the difference spectra improve, which directly improves the signal to noise ratios.

During the spring of 2001 (at the start of the ACE-Asia campaign), the turbopump associated with the detection region was upgraded from a Varian model Turbo-V 70LP to a larger V250 pump, which increased the rate at which gas molecules were removed from this region. Later that year (prior to Pacific 2001), an Alcatel model ATH 30 hybrid pump (later to be replaced with a model ATH 31+, Cedex, France) was added to the skimmer region of the instrument, in addition to the two existing V70LP pumps. This design of pump contains two stages; a turbo-molecular stage similar to the other pumps and a Holweck (drag) stage. The latter stage consists of a fixed helical channel positioned around a rapidly rotating drum, which uses the same axle and motor as the turbo-molecular stage. The gas molecules are driven along the length of the channel by the drag forces caused by the drum's movement.

The hybrid pump does more than simply assist in the removal of gas from the skimmer region; by connecting the exhausts from all the other pumps to its intermediate port (between the turbo-molecular and Holweck stages), the backing pressure of the

turbopumps is reduced further, thereby increasing their pumping efficiencies. Also, as the Holweck stage does not require as low a backing pressure as a turbopump, a much smaller diaphragm pump can be used, which reduces the overall bulk, weight and power consumption of the instrument. Unfortunately, this modification had to be removed during the NAMBLEX campaign due to a technical failure, which in turn caused the backgrounds to increase again.

The AMS used during the ITCT 2K2 campaign was actually a second, newer instrument. The lens and mass spectrometer systems were identical to those of the first instrument but the pumping system had undergone further modifications. The first two turbopumps at the skimmer region and the pump on the detection region had been replaced with Varian model Turbo-V 301 Navigator pumps. As these are more powerful and able to pump a larger volume of gas per unit time, the detection region pressure was reduced further and only one turbopump was needed at the skimmer region.

The adjustable lens design described in section 2.2.1.1. meant that the particle beam could be directed more accurately and therefore the aperture between the second and third chambers did not have to permit as wide a range of trajectory angles. The aperture was extended into a channel of a reduced diameter, reducing the gas conductance between the chambers further and thereby reducing the pressure in the detection region during sampling. Also, when the mass spectrometer was upgraded during the autumn of 2001, a baffle was fitted above the ionisation region around the rods to restrict gases travelling upwards towards the multiplier. This effectively created a new sub-chamber, containing the quadrupole rods and the electron multiplier. An extra V70LP pump was fitted to this region to reduce the pressure even further. This arrangement also helped prevent any lower volatility gases degassed by the vaporiser and filament migrating upwards and subsequently condensing onto the upper stages of the mass spectrometer.

2.2.1.3. Other improvements

During the autumn of 2001 (immediately after the Pacific 2001 campaign), the quadrupole system was upgraded from a Balzers model QMA 400 to a QMA 410. The 410 uses longer and wider rods (16 mm diameter instead of 8 mm), which improved both the m/z resolution and the fraction of ions transmitted, especially in the high m/z regime. According to the manufacturer, there should be no difference in the relative sensitivity as a function of m/z within the range that is used by the AMS.

Originally, the chopper wheel shipped with the instrument had a duty cycle of 3.5 %, i.e. the slits occupied 3.5 % of the circumference of the wheel. During the improvements to the vacuum system during the summer of 2001, it was deemed that the overall sensitivity of the instrument had been sufficiently increased to warrant changing the 3.5 % chopper for a 2 % version. This reduced the overall amount of particulate material being detected in TOF mode and therefore the signal to noise ratio, but increased the sizing resolution.

In addition to the mass spectrometer upgrade, the flat molybdenum vaporiser coated with multiple layers of molybdenum mesh was replaced with an 80 % porous tungsten heater in an inverted cone shape. This was changed to reduce the possibility of particles bouncing off the heater without vaporising. Also, the inverted cone is angled so that the vapour plumes are directed more towards the optimum detection volume of the quadrupole, meaning that the instrument sensitivity to individual particles does not vary as much with respect to their impaction sites on the vaporiser.

For the ITCT 2K2 experiment, the UMIST AMS was temporarily modified to be able to detect sea salt particles. In the standard configuration, it is possible to run the vaporizer at a high enough temperature to vaporize sodium chloride particles, but at these temperatures a significant proportion of atoms such as sodium and potassium become ionized thermally on the surface of the vaporiser rather than by electron impact. Surface ionization is very undesirable in the AMS because it produces positive ions in very large numbers and does not easily yield quantitative data. Several laboratory experiments were conducted at ARI to optimize the AMS in order to measure the sea salt aerosol composition present in ambient aerosol. The modification of the AMS consists of physically moving the vaporizer 3 mm away from the quadrupole detection region, adding a negative bias voltage until the background sodium signal becomes very low and operating it at a temperature of about 850 °C.

In this configuration, any positively charged ions produced by the vaporizer are unable to overcome the potential difference between the surface of the vaporizer and the ionization region, and so only the neutral atoms are able to reach the detection region. These are subsequently ionized by electron impact and are detected. The trade-off was that the instrument's overall sensitivity was reduced, due to both the increased distance between the heated surface and the detection region and the fact that the vaporized molecules, having a higher thermal velocity, spent less time in the detection region

compared with the standard configuration. While this reduction in sensitivity was accounted for by the calibration protocol, it in turn affected the signal to noise ratios of the data. Also, the high vaporizer temperature meant that organic species were subject to additional thermal fragmentation, making the mass spectral identification of the types of organic chemicals in the particles more difficult. After this deployment, the instrument was returned to the standard configuration for general-purpose use.

2.2.2. Particle collection issues

In the laboratory, it has been noted that when the number concentration of particles in a monodisperse aerosol flow is measured by both an AMS and a CPC, the agreement between the two instruments is dependent on the particle composition. The ratio of the number concentration counted by the AMS to the CPC is known as the collection efficiency. It was discovered that this collection efficiency number is highly dependent on the phase of the particles.

For example, the AMS detects particles composed of dioctyl phthalate and oleic acid with 100 % efficiency, but for adipic acid and succinic acid, the efficiency is 15 % or less (M.R. Alfarra, UMIST, unpublished laboratory data, 2003). The main difference is that the former two species form liquid droplets under laboratory conditions, while the others are solid. Similarly, when generating inorganic particles in the laboratory, ammonium sulphate's efficiency is normally around 20-25 %. The efflorescence point of this chemical has been estimated at around 37-40 % RH [Tang and Munkelwitz, 1994], so it is most likely that while although the particles are generated in the aqueous phase in the atomiser, they are being subsequently dried out by the carrier gas or the DMA sheath gas to form solid particles.

The exception to the solid versus liquid pattern is ammonium nitrate, where counting efficiencies of 90- 100 % are typically achieved. This species' efflorescence point has been estimated as much lower than sulphate, at 25-32 % RH [Tang, 1996]. While it is possible that the conditions could be reached where ammonium sulphate particles are dried but ammonium nitrate particles left aqueous, the DMA sheath gas used in the UMIST lab is typically at less than 5 % RH, which would effloresce both.

During field measurements, it has been found during comparisons with other chemistry instruments, the AMS has tended to underestimate the total loadings of chemicals, most notably sulphate, by about a half when using its own calibration values (see section 2.2.2.1.). Under most conditions during ambient sampling, the line leading

up to the instrument is heated conductively by the turbopumps, which decreases the RH of the sample flow. This warming, compounded by the fact that the cabin is often warmer than the ambient air, will dry out the ambient particles, possibly causing them to form irregular solid particles. Interestingly, this collection efficiency of 50 % has been consistent between a number of different sites, times of year and instruments. As a result, most reported data have included a correction for this. However, it has been known to vary on some occasions, sometimes giving values close to 100 % [e.g. *Boudries et al.*, 2004].

While it has been shown that the aerodynamic lens system used in the AMS can focus spherical particles very efficiently [*Jayne et al.*, 2000], it is generally accepted that non-spherical particles will tend to form divergent beams rather than the tightly collimated ones desired, due to lift forces on the particles that act perpendicular to the air flow. *Liu et al.* [1995a] made some theoretical predictions for simple geometries, but modelling work for atmospheric particles is difficult due to uncertainties and irregularities in their shapes. It is suggested that some solid particles may form non-spherical shapes, as has been seen in electron microscopy, that may become significantly defocused so that a significant fraction may not be collected on the vaporiser.

At the time of initial submission of this thesis, the hypothesis mentioned in the previous paragraph was the principal candidate mechanism for the reduction in collection efficiency associated with many types of solid particles. As a result, the majority of this work has concentrated on evaluating this phenomenon further. However, investigations have since shown that while this defocusing of various particle species is a real phenomenon, the losses typically account for less than 5 % of the total signal [*Huffman et al.*, 2004]. The current favoured theory at the time of writing is that the solid particles are bouncing or otherwise becoming detached from the surface of the vaporiser without becoming successfully vaporised, while the liquid particles are sticking correctly. Work to investigate this is ongoing.

2.2.2.1. Temperature cycling findings

The first direct evidence for the improvement in collection efficiency for liquid particles in ambient particles was noted during the ITCT 2K2 campaign in the spring of 2002, which is presented in section 3.2.2. of this thesis. As part of the deployment, one of the AMSs used was fitted with a method of temperature control on its inlet. Water

was recirculated around the assembly containing the critical orifice at the instrument's inlet and the tubing leading up to the instrument (figure 2.2.2.1.a). The water was fed from a refrigerated bath, maintained at 2 °C, passing over an AC heating coil.

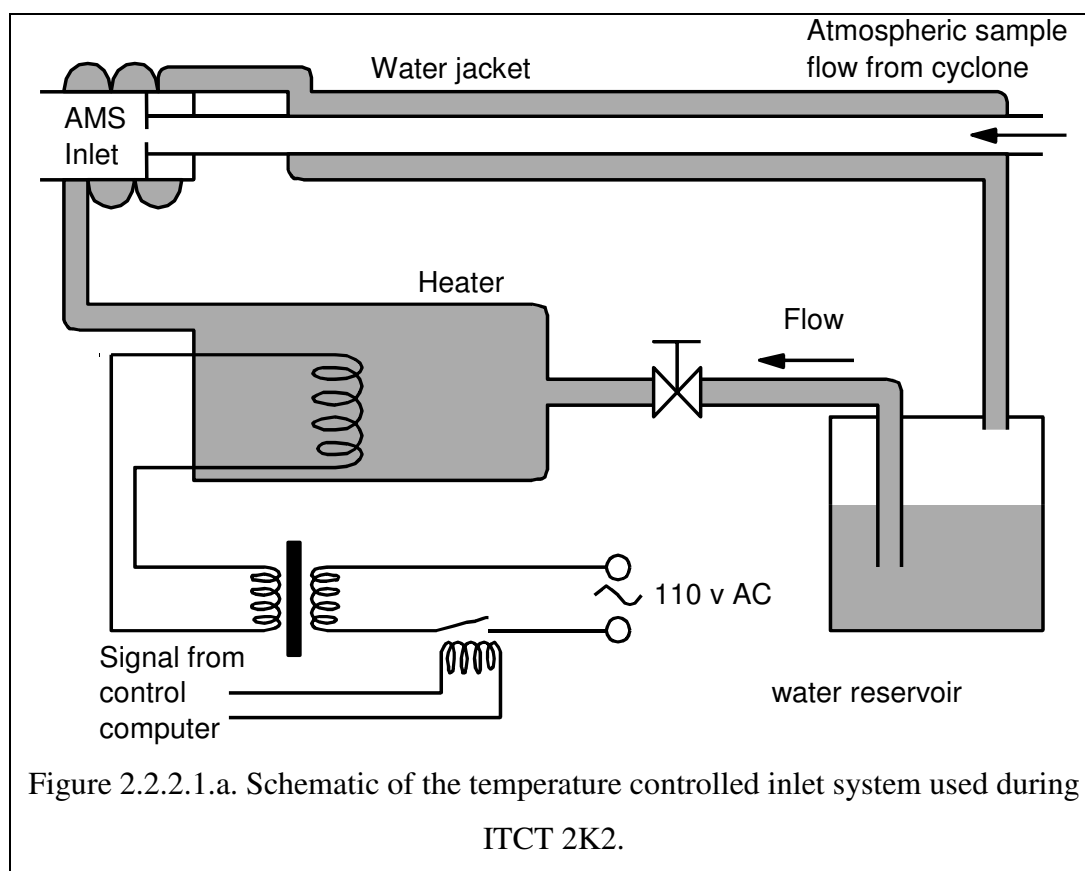
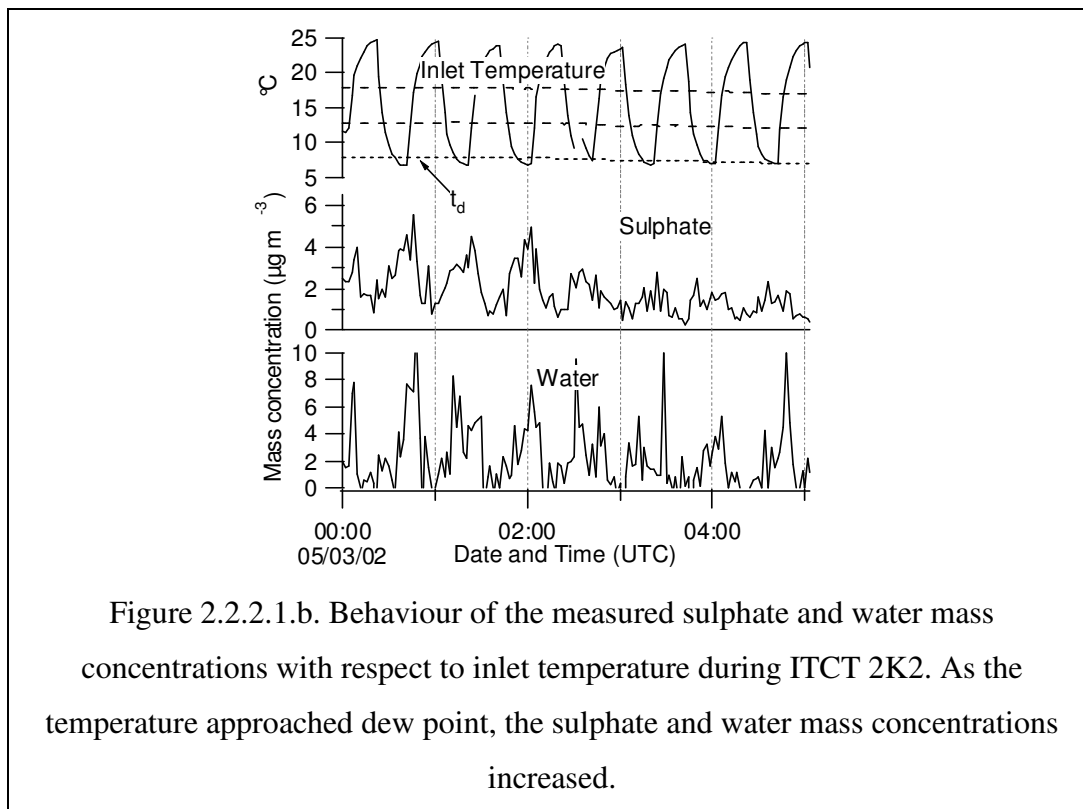


Figure 2.2.2.1.a. Schematic of the temperature controlled inlet system used during ITCT 2K2.

The temperatures of the inlet and recirculating water were measured using thermocouples (OMEGA Engineering Inc., CT, USA), interfaced to the logging computer. The power to the heating coil was switched on and off digitally on a forty minute cycle, which ramped the inlet temperature up and down. By adjusting the water flow rate and the voltage applied to the heating coil, the magnitude and the ramp rate of the temperature cycle could be adjusted. Generally, the low extreme of the cycle was matched to the ambient dew point and the high extreme to approximately 20 °C above this. The dew point temperature (t_d) data were calculated using ambient temperature (t) and relative humidity (RH) data from a solid-state probe (model HMP45C, Campbell Scientific Inc., Logan, UT, USA) located on the sampling tower that mounted the inlets.

When the line temperature is low and close to the dew point, the measured amount of water increases (figure 2.2.2.1.b). The total mass of water in both the gas and particle phases entering the instrument is not altered by the inlet temperature but the majority of the gas phase material is removed by the skimmer, suggesting that water is condensing into the particle phase in the line at these temperatures. This also provides

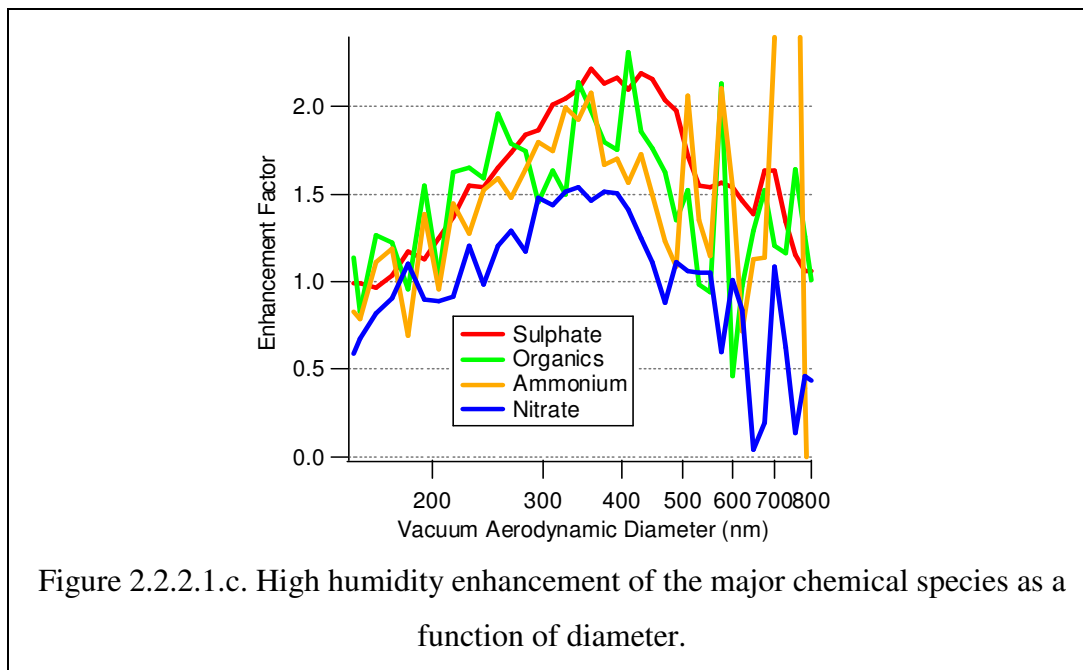
evidence that although the particles are exposed to very low pressures in the lens and the rest of the instrument, they do not have enough time to dry out completely. If the particles were deliquesced when they are focused and accelerated, this would explain the apparent increase in the amount of sulphate detected, either through improved focusing or lack of bounce.



To facilitate interpretation, the data were separated according to the difference between the inlet temperature and the ambient dew point ($t - t_d$) and then averaged into 1 hourly periods. The two data series presented are those for occasions where the difference was less than 5 °C and when it was greater than 10 °C. These temperatures were chosen because with the setup used, the pinhole temperature spent the majority of its time in these two bands, with rapid transitions between them (figure 2.2.2.1.b). While it is accepted that this is a very crude method of studying particle hygroscopic behaviour, the setup used in this experiment did not have sufficient precision in the temperature and humidity measurements to permit a more thorough analysis.

When comparing the low $t-t_d$ time series with that of the high $t-t_d$, an enhancement can be seen in the low difference series of roughly a factor of 2. This enhancement can be seen in the averaged TOF data (figure 2.2.2.1.c). However, while there is an increase in the mass loading of the chemicals, there is no apparent change in the vacuum aerodynamic diameters of the modes. When looking at the enhancement

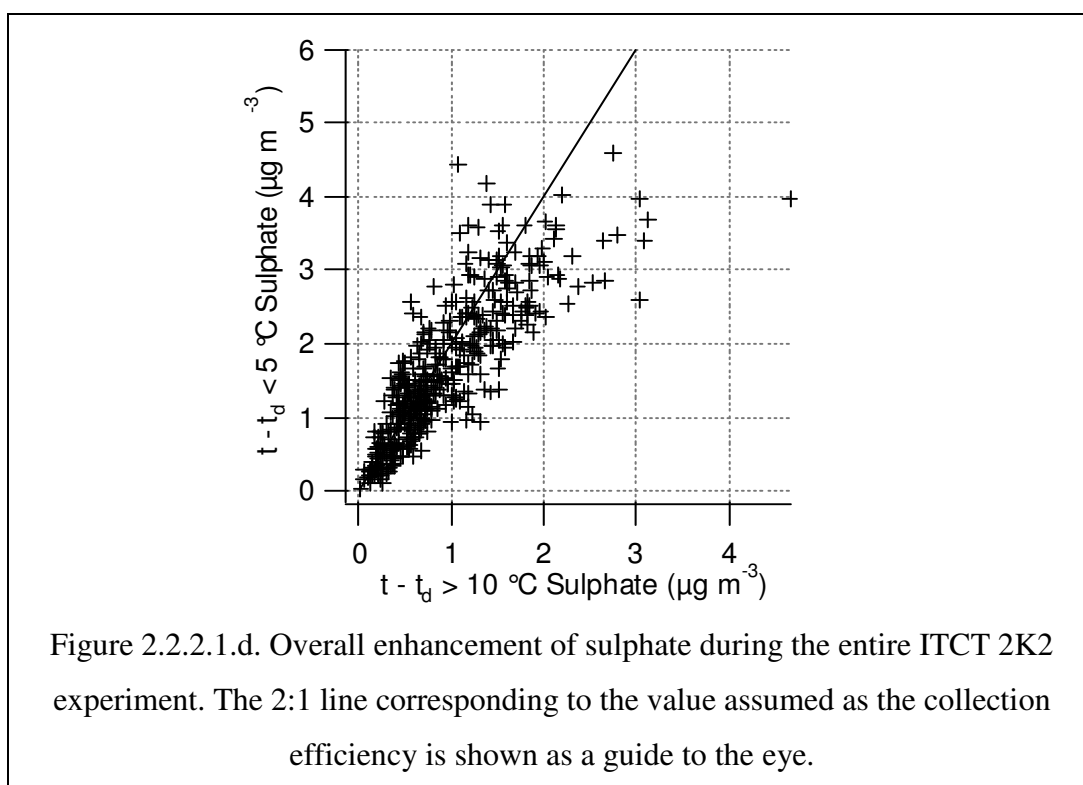
factor as a function of diameter, sulphate, ammonium and the organics are all enhanced by a factor of two at the modal diameter. At lower diameters, the enhancement is smaller. Nitrate behaves slightly differently in that its enhancement is only around 1.5. Also, there is an apparent suppression of the nitrate loadings in the coarse mode when the temperature approaches the dew point.



It would be expected that as the particles take on water, the physical size of the particles must increase also, as seen by HTDMAs. However, no noticeable size change was observed with the AMS. This is a property of the fact that as discussed in section 2.4.3.1., the instrument measures vacuum aerodynamic diameters, which are proportional to the particle densities. As a particle takes on water, its D_v increases, but if the solute is of a density greater than that of water, the overall density will decrease. For salts such as ammonium sulphate, the effects cancel each other out and result in the vacuum aerodynamic diameter being largely invariant in sub-saturated humidities for a given amount of solute [Matthew and Middlebrook, 2003].

Note that the enhancement factors decrease towards 1 at lower diameters. The cooling method relies on the assumption that the particles remain aqueous until they are focused but it is known that at least some of the moisture vaporises within the lens itself [Buzorius *et al.*, 2002]. While this is not a problem for the larger particles, the smaller ones may dry out and be focused dry, therefore having a collection efficiency of less than 1. However, as these particles represent only a small fraction of the total mass, the overall loadings aren't significantly affected.

The enhancement at low $t-t_d$ in the sulphate series in particular can be seen in the scatter plot in (figure 2.2.2.1.d). A line representing an enhancement factor of 2 is included as a guide to the eye. Most of the data points follow this line, with a few significant departures where the enhancement is lower. These may be due to the detection of metastable particles that had not effloresced at the higher temperatures, or not deliquesced at the low temperatures. While it is accepted that limitations in the control and monitoring hardware used in this case hinder detailed investigations into the hygroscopic behaviour, this may give some insights into the detailed chemical nature of particles present.



The lower enhancement factor in the nitrate could be explained by the presence of more than one form of nitrate being observed, which seems to be the case, given that it exists in both the coarse and accumulation modes, unlike the other components. The apparent suppression of the coarse mode at low inlet temperature is probably due to the way the larger particles are lost in the inlet assembly of the AMS. It has been predicted using computational fluid dynamics that particles larger than around 0.7 to 1 μm will be lost due to impaction with the inner walls of the tubing as they leave the pinhole, with the effect being more pronounced for particles with larger aerodynamic diameters [Zhang *et al.*, 2004]. However, what the computer model does not take into account is the fact that particles may bounce when they hit the wall and become re-entrained in the

airflow. *Topping et al.* [2004a] reported loadings at particle sizes of around 2 to 3 μm , which are larger than the theoretical limit predicted by the computer model.

If this bounce phenomenon in the pinhole region is real and significant, it would be expected that dry particles will be more likely to bounce off the stainless steel tubing than aqueous ones. This would explain the suppression of the measured the coarse mode loading when the temperature approaches dew point. Also, the spray effect at the pinhole that causes the impaction of the particles occurs at a higher pressure than the nozzle acceleration, so is more dependent on the ‘classical’ aerodynamic diameter of the particles. Unlike the vacuum aerodynamic diameter, this is less dependent on particle density and therefore increases as particles grow hygroscopically and so the loss effect will be even more pronounced for deliquesced particles. As discussed in section 3.2.2.2., the nitrate in the larger particles was found to be in sea salt particles, which will be more susceptible to this effect than the sulphate-based particles, as they typically manifest larger growth factors [*Berg et al.*, 1998]. The enhancement factor of the accumulation mode nitrate being less than that of the other components is probably due to the bimodality of the nitrate distribution and the enhanced accumulation mode crossing over with the suppressed sea salt mode distribution.

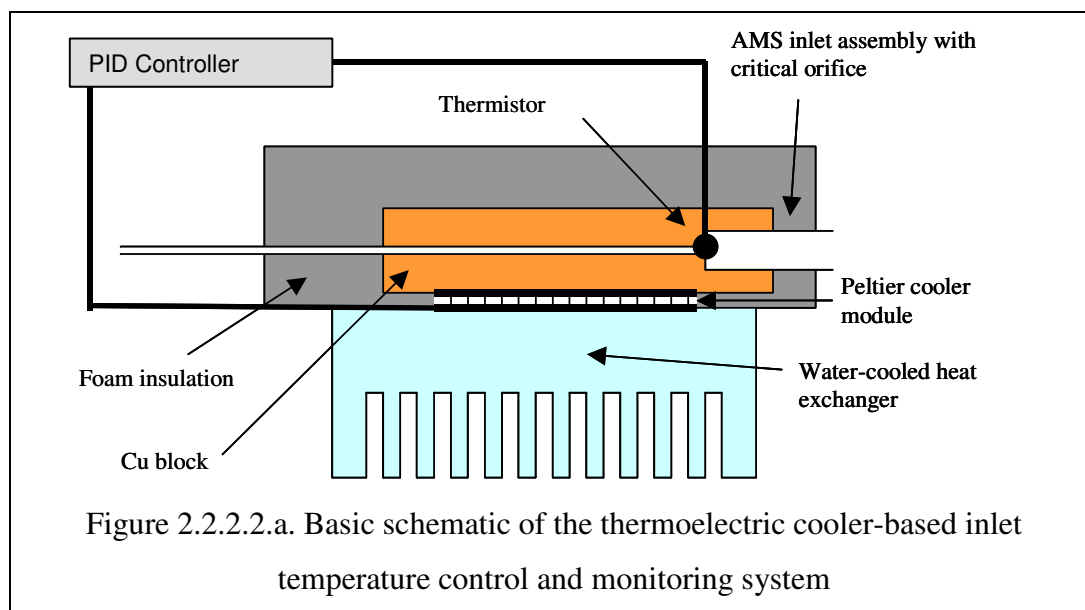
2.2.2.2. Thermoelectric temperature controller development

As a result of the discovery of the importance of the relative humidity of the sample flow to the AMS measurements, it was deemed vital to be able to monitor this during future measurements and possibly control it with a view to mitigating the collection problems. Work was undertaken to develop a solution to this with a view to using it in future lab and field experiments.

The possibility of passing the sample flow through a semi-permeable membrane tube within a concentric humidified flow on the outside was considered. However, during preliminary testing it was found that small particles were frequently lost to the inner surfaces of the tubing in a manner not independent of particle composition (*M. Cubison*, UMIST, personal communication, 2002), so this idea was abandoned on the grounds of adding too many extra uncertainties. Also, these systems are very difficult to control precisely.

Another solution considered was to control the humidity of the sample flow through controlling the temperature, as used during ITCT. However, instead of using water to control the temperature, a thermoelectric cooler was used. These are Peltier

devices that consist of an array of bismuth telluride semiconductors between two parallel ceramic plates. The semiconductors are arranged electrically in series, alternating between p and n type according to the direction between the plates the current will flow. This configuration acts to pump heat between the two surfaces when a DC voltage is applied. The advantages of this design over the water cooler are numerous; they are highly controllable with fast response times, the amount of bulk is reduced and the need for complex plumbing is eliminated.



The instrument's pinhole assembly and the tubing leading up to it were fitted inside a copper block (figure 2.2.2.2.a). Using a material with a high heat conductance reduces the magnitude of any temperature gradients that may form during operation. The copper block is insulated using expanded polystyrene. At least 60 mm of the tubing leading to the pinhole is contained within the block, as this was calculated to be sufficient to allow enough residence time for the air flow to cool diffusively throughout (*M.J. Flynn*, UMIST, personal communication, 2003). The cooler itself (Marlow Industries Inc. model AT12-6, Dallas, TX, USA) is held in a compression fitting between the copper block and a heat exchanger, using heat conductive pads to correct for imperfections in the surfaces. The heat exchanger consists of PVC tubing wrapped around a finned aluminium block. Water is recirculated around this to transfer heat away from the assembly and to a reservoir located in a cooler location (e.g. outdoors).

The cooler is controlled by an Oven Industries model 5C7-362 controller (Mechanicsburg, PA, USA.), which delivers a 12 V 2.7 kHz pulse-width modulated signal to the cooler. While a thermoelectric cooler can be controlled by varying the voltage of a constant DC supply, a pulsed signal of a constant voltage but variable duty

cycle is electronically more efficient and easier to generate and control. The controller uses a feedback loop and proportional-integral-differential control to maintain the temperature at a given setpoint, although it was found that the response time of the apparatus is short relative to the time scales of any perturbations, so the differential component is not needed and it is operated in proportional-integral mode instead. The temperature is measured using a bead thermistor located in the copper block near the pinhole, which is connected directly to the controller module.

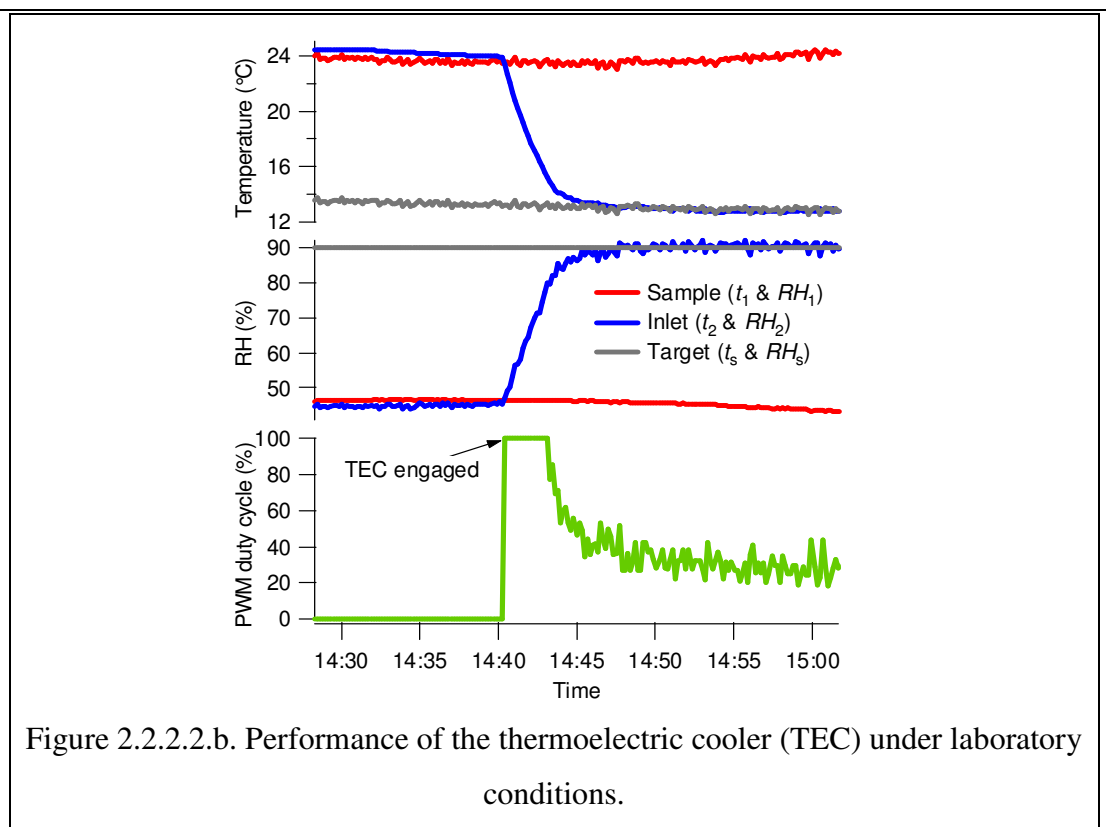
Software written to interface with the controller and log the behaviour was written at UMIST and used Igor Pro version 4 (Wavemetrics Inc., Lake Oswego, OR, USA) as a platform. This communicates with the controller using an RS232 (serial) interface. The software uses temperature (t_1) and relative humidity (RH_1) measurements from either the ambient air or a sub-sample of the sample flow in order to measure the dew point of the aerosol. A Rotronic Hygroclip SC05 probe (Crawley, West Sussex, UK), connected to the logging computer's data acquisition system, is used for this purpose. The setpoint temperature required (t_{RH}) for a given setpoint relative humidity over water (RH_s) is calculated using the following equation, adapted from the Magnus equation [eqn. A.4-2, in *Pruppacher and Klett*, 1997, pp. 854], and the controller's setpoint is continuously updated. Note all temperatures are in °C.

$$t_{RH} = \frac{234.9A}{17.5 - A} \quad A = \ln\left(\frac{RH_1}{RH_s}\right) + \frac{17.5t_1}{234.9 + t_1} \quad (2.2.2.2.i)$$

The temperature of the inlet line (t_2) is measured using the thermistor and the relative humidity of the aerosol sample flow at this point (RH_2) are estimated using the following rearrangement of the same formula:

$$RH_2 = RH_1 \exp\left(\frac{17.5t_1}{234.9 + t_1} - \frac{17.5t_2}{234.9 + t_2}\right) \quad (2.2.2.2.ii)$$

Operationally, the apparatus performed very well. As shown in figure 2.2.2.2.b, the inlet temperature was reduced to the setpoint in less than ten minutes after the cooler was switched on in a lab environment. Also, the temperature was held steadily at the setpoint, so that the relative humidity was kept at the desired value of 90 % with a standard deviation of 0.97 %.



To test the effectiveness of the apparatus in improving the focusing of the particle beam and probe the general particle beam shape, the AMS was fitted with the cooler during the QUEST 2 field campaign at Hyytiälä in Finland during March and April 2003 [Allan *et al.*, 2003c; Allan *et al.*, 2004a], an experiment that is not covered in detail by this thesis. A movable wire similar to that described by Jayne *et al.* [2000] was used, which consisted of a 0.5 mm diameter wire, located just before the detection region aperture at the end of the TOF region, that was moved in and out of the particle beam using a servo motor. This alternated between seven positions within the beam and an unblocked position on a two-minute basis. The inlet was kept at 90 % RH during sampling for the second half of the field campaign. This humidity was chosen because this is much greater the deliquescence point of ammonium sulphate (79.97 % at 298 °K [Robinson and Stokes, 1955]), but less than saturation, to avoid particle activation or water condensing on the tubing or pinhole surfaces. The temperature was also not allowed to go below -5 °C, to prevent supercooled droplets contact freezing or water vapour subliming onto the pinhole and potentially blocking it.

By comparing a measured signal at a given position to that of the unblocked position, the fraction of particles within that sector of the particle beam could be measured. Figure 2.2.2.2.c shows the percentage of sulphate mass in each sector, averaged over two particle events, one immediately before the cooler commenced

operation and one immediately after. While these are only two particle events, they are representative of the general behaviour before and after the cooler activation. Before cooling, the beam is quite wide, with the sulphate mass distributed across all of the sectors. After the inlet relative humidity is reduced to 90 % however, the majority of the mass becomes contained in the centre sector, so it is reasonable to assume that the collection efficiency is close to 1. Note that the percentage does not completely fall to zero in the other bins; this could be due to the small particles discussed in section 2.2.2.1.

